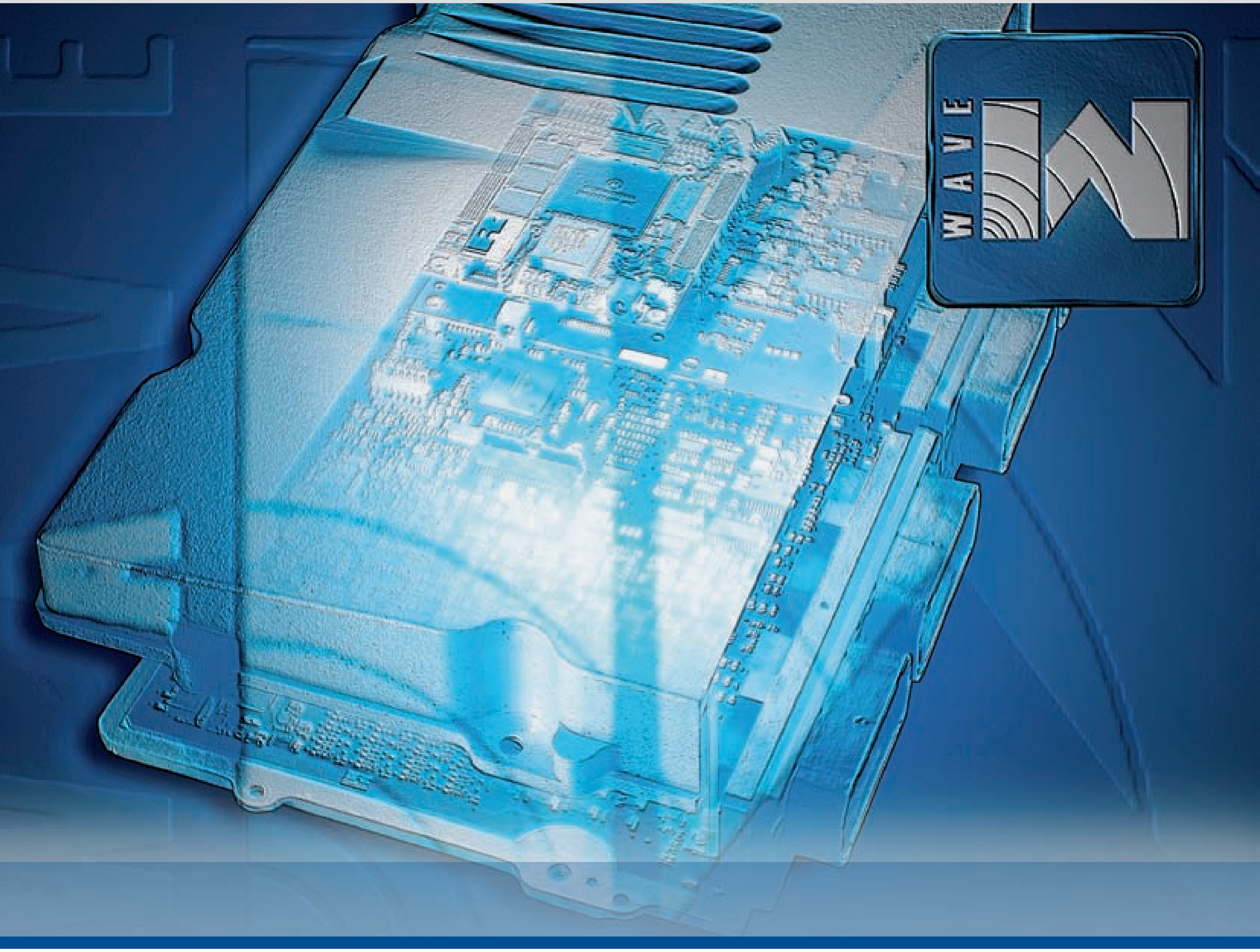

Crank Angle-resolved Realtime Engine Simulation for the Optimization of Control Strategies

An engine simulation model permits new control strategies to be optimized at an early stage. The simulation tools used typically offer either the speed necessary for HiL tests or alternatively a high degree of accuracy. Ricardo has now developed a software tool with the capability to bridge the gap between these tool types and to address the growing demands made on engine control accuracy. The tool has been validated using a 1D model of a four-cylinder diesel engine currently in series production.

1 Introduction

In order to further reduce fuel consumption and emissions in the vehicles of tomorrow, more efficient engine control systems based on new control strategies and system architecture models are essential. To develop this type of increasingly complex control system quickly and achieve the necessary maturity level at an early stage, an efficient method of engine simulation is essential. It is only by using an engine model that the behaviour of new control components can be efficiently verified and optimized. Ideally, developers should have access to a seamless tool chain for design, development and testing. A number of different framework conditions pose a challenge here: As simulation-based real-time testing of a new control system is conditional nowadays on the existence of a parameterized engine model, optimization can only be achieved through simulation if mapping is available, **Figure 1**. Verification of Hardware-in-the-Loop tests (HiL tests) requires the existence of a real-time model which, due to the stringent demands made on its running speed, has so far tended to compromise the precision of results. At the same time, however, HiL tests have a major role to play in ensuring correct control system operation. To a certain degree, it is also possible to carry out a virtual calibration process already on the HiL test bench, a process which can cut short development periods and under certain conditions also increase engine performance [1, 2].

A transition from map-based control systems to increasingly model-based control systems appears highly likely in the future. Ideally, this type of calibrated model would have to be stored in the ECU and run in real time alongside parallel test bench experiments. This method would allow the model-based control strategies to be supplemented to include for instance model-based compensation of engine ageing effects by comparing the simulation with the physical test.

Additional control variables such as valve stroke and timing, turbine blade position in variable turbine geometry (VTG) turbochargers, multiple injection and others increase the model complexity still further. The same applies to new combustion methods such as diesel homogeneous charge compression ignition (HCCI), which call for closed-loop engine control within the narrowest tolerance window and consequently require simulated engine sequences with an extreme degree of precision. The already foreseeable need to combine real-time capability with a high degree of precision in a single model demands a new tool which will more closely interlink the development and test phases.

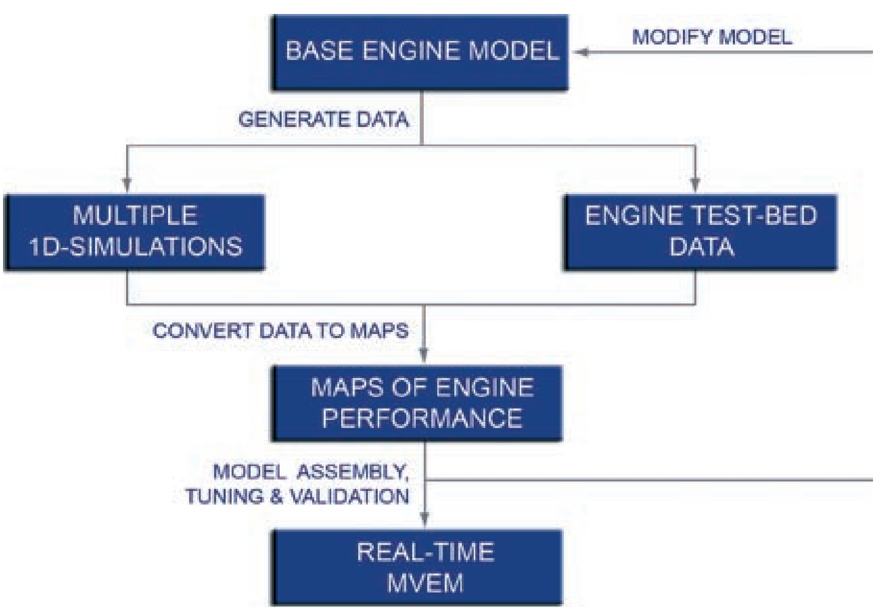

Figure 1: Schematic view of an MVEM parameterization process

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Table 1: Factors of the RT model simulation speed measured with an increment of 27.78 ms (= 1° crank angle at 6000/min); a factor of 0.5 denotes double real-time running speed

Platform	Fraction of RT Speed
Intel Xeon CPU 2.4 GHz	1.61
Intel Pentium 4 CPU 2.8 GHz	1.37
Intel Xeon CPU 3.6 GHz	0.91
AMD Athlon 64 X2 Dual Core Processor 4600 +	0.75
Intel Xeon CPU 5160 @ 3 GHz	0.36

2 Outset Situation

Today, engine simulation typically takes place using a mean value engine model (MVEM) or in the form of distributed parameter models. Both types of model have their own specific benefits and drawbacks:

- MVEMs of the kind customarily used for HiL tests are fast enough to comply with tough real-time requirements and also precise enough for testing present-day engine control systems. However, these models calculate all the cylinders with identical values and portray the cyclical fluctuations of the mass flow in the air pathway using a constant approximated value. This clearly restricts their efficiency. MVEMS are just as unsuitable in their design for calculating cylinder-specific optimization strategies or even cylinder pressure-based combustion control as they are for precise capturing of transient engine aspiration behaviour, for instance in the case of variable intake manifolds or multi-turbochargers.
- The benefit of phenomenological combustion models is that they depict sequences in the cylinder. However, they are unable to provide modelling of the wave propagation effect in the air pathway, which diminishes their ability to accurately reproduce transient behaviour [3].
- Artificial neuronal networks are good for the precise prediction of complex processes [4], but restrict the view of underlying physical processes and consequently prevent observation of the effect of individual interventions.
- One-dimensional distributed models such as Ricardo Wave, GT-Power and AVL-Boost model the complex processes taking place in the intake duct and combustion chamber to a high degree of precision. However, the computation speed for these models is over 40 times longer than is required for real-time simulation.
- While three-dimensional models such as Wave 3D, Kiva or Vectis provide the greatest prediction quality due to their extremely fine resolution of flow processes, the extreme demands they make on computing performance mean that they are generally reserved for the detailed examination of individual components or for simulation of processes in the combustion chamber.

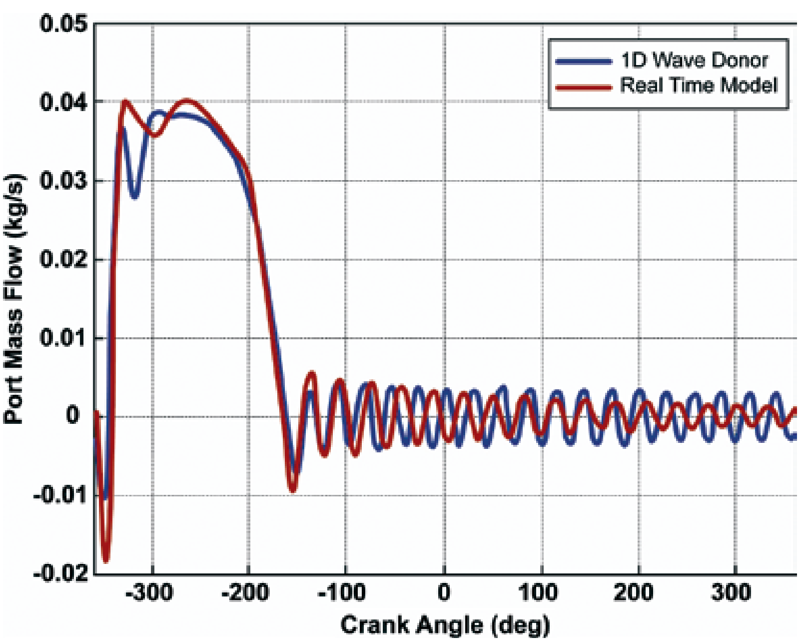

Figure 2: Simulation comparisons of volumetric port air flows using an 1D-WAVE donor model

3 Crank Angle-resolved Real Time Engine Simulation

In view of the ever more stringent demands imposed on the development of engine control functions, Ricardo has developed a new software which permits real-time engine simulation to a high degree of accuracy. Using a distributed mathematical 1D model generated in Wave, the software creates a Wave real-time model (RT model) which, depending on the processor, runs on standard PC systems at up to three times real-time speed, **Table 1**, and which is planned to be capable in the future of also running on Hil systems.

The new software is based on the physical processes taking place in the engine, provides crank angle-resolved, cylinder-specific combustion chamber models and also registers wave propagation in the air pathway. Consequently it is able to depict reactions to transitional statuses with considerably greater accuracy than conventional MVEMs. At the same time, the software is configured for use on HiL test benches. High-speed mathematical functions and polynomials replace both complex computational processes and look-up tables (for instance turbocharger maps [5]) and so accelerate the simulation process.

Conversion of the Wave donor model into the RT model is performed automatically within seconds by software belonging to the simulation tool. This sequence

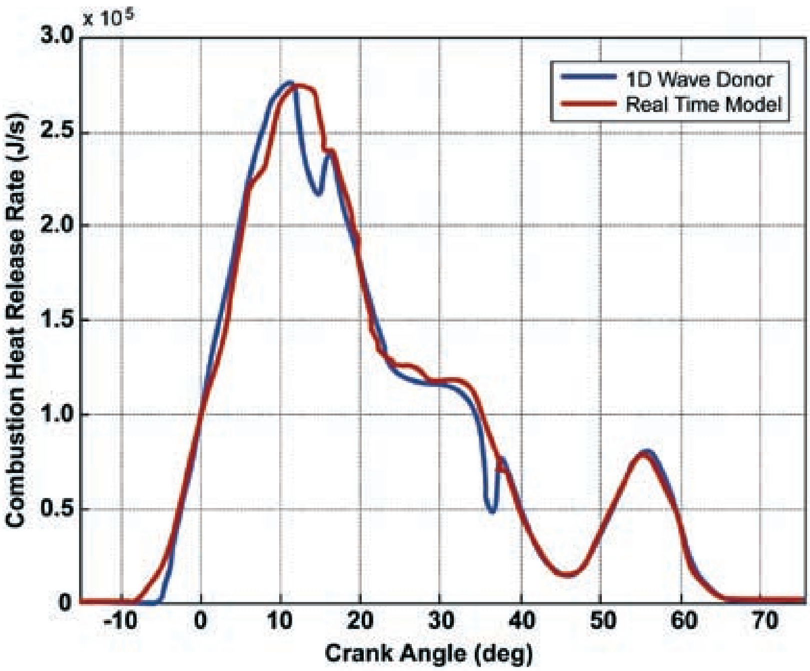

Figure 3: Heat release rate during multiple injection with three injection pulses

permits the engine to initially be precisely modelled before the RT version is generated from the 1D model within the seamless tool chain.

The RT model simulates sequences in the engine using conventional differential equations and an integration algorithm (solver) with fixed steps, which calculates the flow dynamics in the individual sections of the air pathway based on mean values, whereby the capacitative flow characteristics (mass, pressure and temperature) are described as finite volumetric elements, while their inertia behaviour (i. e. mass and energy flow) are separately calculated within the individual sections of the air pathway. This combination permits the flow dynamics to be depicted. The dynamic correlation between pressure values at the start and end of the air pathway section and the mass flow in the air pathway were implemented based on the work of Cipollone and Sciarretta [6, 7]. Simulation comparisons between the 1D donor model and the automatically generated RT model already show a high degree of correlation, **Figure 2**.

The combustion model is based on exponential equations of the released thermal energy and is calculated separately for each cylinder with up to six injection pulses per work cycle. **Figure 3** illustrates the progression of heat release for a combustion process with three injection pulses. There is a mathematical reason for the sharp deviations in the 1D model at crank angles of 12° and 35°: The equivalent of the injected fuel exerts an immediate influence on the 1D model, while this is not calculated until the end of the injection process in the RT model. Despite all the outlined benefits, the new simulation is subject to restrictions in two respects:

- In the interests of optimizing computation speed, a large number of approximations are used. At certain points of operation this can compromise simulation of the 1D model values to a certain degree.
- Use of the new software calls for a certain level of expertise in RT methodology in order to permit the development of a donor model which is ideally suited for the generation of a good RT model.

4 Validation of the Real-time Model

To test the accuracy of the RT model, it was applied on a 2 litre four-cylinder diesel engine with VTG turbocharger, intercooler and exhaust gas recirculation (EGR), and the simulation results of the 1D-Wave engine model compared to the results of the RT model generated from it. For the purposes of this paper, it should be borne in mind that development of the RT model had not yet been completed by the date of validation. Four operating points were each tested at the speeds for maximum torque (2000/min) and for rated output (4000/min) under full and partial load conditions. In addi-

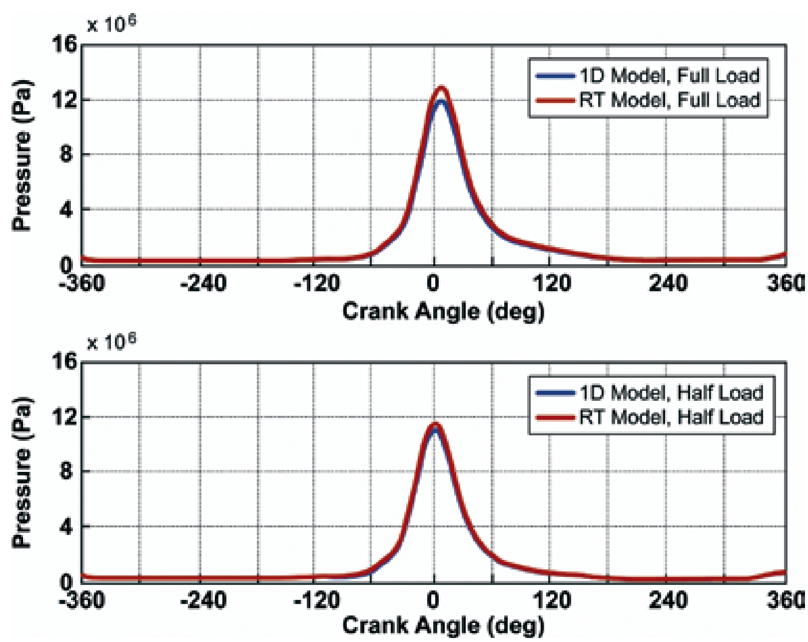

Figure 4: Pressure in the simulated cylinder 1 at 4000/min, full load above, partial load below

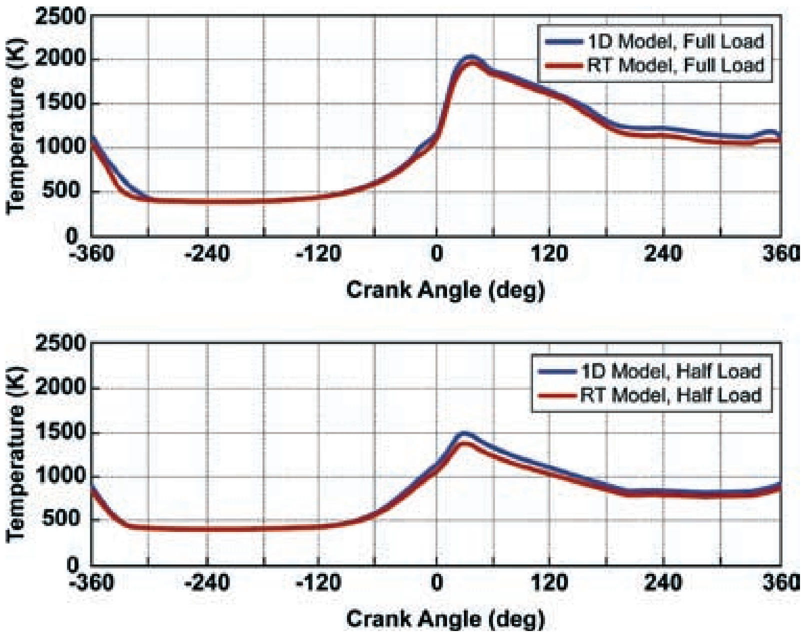

Figure 5 : Temperature in the simulated cylinder 1 at 4000/min, full load above, partial load below: 1D model = blue curve, RT model = red curve

tion, for each speed a heat release curve is plotted. The pictures below compare the curve progressions of the 1D model and the RT model.

Overall, the two models agree very precisely despite the fact that qualitatively satisfactory modelling of the cylinder wall temperature was not yet available (cf. Section 5). Consequently this factor had to be assigned a fixed value (480 K). **Figure 4** illustrates the simulated pressure development in cylinder 1 at 4000/min. The in any case minimal tendency of the RT model to set the combustion chamber pressure too high would be reduced given good modelling of the cylinder wall temperature. **Figure 5** substantiates the agreement between the two models as regards simulation of the temperature development. **Figure 6** shows a comparison of the curve progressions for the indicated torque level. Finally in **Table 2**, a summarized overview of all observed percentage errors of the RT model for the simulated parameters.

5 Summary

HiL tests using an engine model with real-time capability help eliminate the breach between good model accuracy during the development phase and diminished accuracy during the test phase. Automatic conversion of the 1D-Wave model into the Wave-RT model offers the potential to accelerate development, as model-based real-time simulation can be used at a considerably earlier stage, and with greater speed and flexibility than time-consuming mapping processes. Consequently, verification of the real-time model is far simpler, as it can be very efficiently performed by a quick comparison of results with the Wave "parent model." Another benefit lies in the fact that the 1D modeller has the capability to generate the model, as complex 1D-Wave models and Wave-RT models are created and matched by the same engineer. The new software tool permits engine control strategies to be verified and optimized at an earlier juncture in the development process, rendering delays due to the late discovery of anomalies unlikely. It will be available later in 2008 as a component of Wave 8.1.

6 Outlook

A direct comparison of development times using conventional procedures and using the new software is not yet available. Quantitative analysis of possible optimization potential as control strategies are developed has already begun. The RT model is being further refined in terms of both functionality and speed. Current projects include work on modelling of the cylinder wall temperature. Work is also in hand to optimize the code for more efficient computing capacity utilization. This is due to be followed by further refinement of the software component for generation of the RT model.

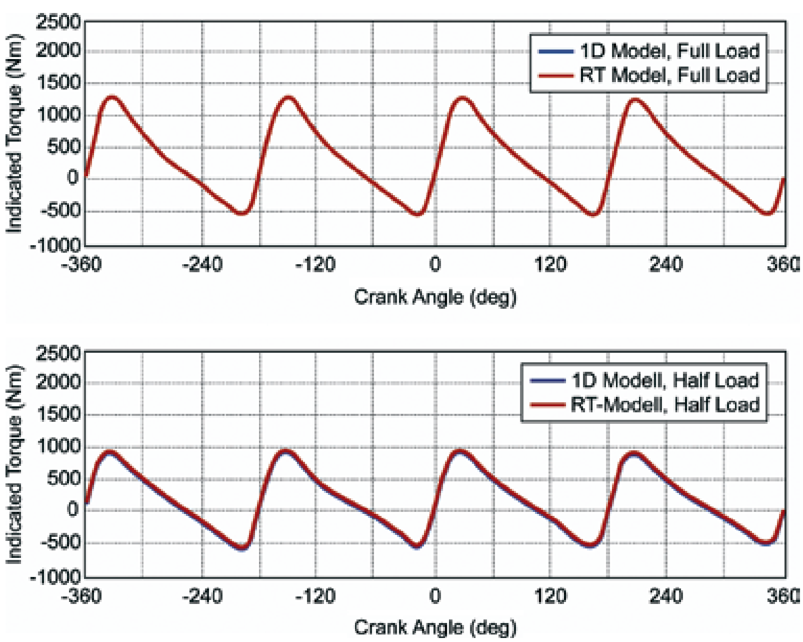

Figure 6: Indicated engine torque at 4000/min, full load above, partial load below

Table 2: Error percentages for peak values of simulated variables for the individual test points

Model Output	2000 rpm full load	2000 rpm half load	4000 rpm full load	4000 rpm half load
Pressure	6.43	- 1.17	7.25	4.85
Temp	2.70	0.19	- 3.80	- 5.50
Mass	- 3.09	- 3.97	4.46	4.35
Heat Release	- 0.10	0.94	- 1.65	- 0.20
Indicated Tq (+ ve)	1.71	- 1.59	2.82	- 0.04
Indicated Tq (- ve)	- 8.37	- 8.92	- 5.77	- 5.55

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